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RESEARCH DEPARTMENT

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USE OF A LINEAR MATRIX TO MODIFY THE COLOUR ANALYSIS CHARACTERISTICS OF A COLOUR CAMERA

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SUMMARY

A substantial degree of improvement in the colour fidelity of a colour camera can be effected by the use of a linear matrix inserted in the signal chain at some convenient point before gamma correction. Calculations have indicated that the colour fidelity obtained from fairly broad analysis curves when such a matrix is used is superior to that which would have been obtained using the narrow analysis curves specified in TV/126 and TV/148. Moreover, the cost in terms of signal-to-noise ratio or sensitivity is very small, and is less than would result from the use of the narrow curves specified in TV/126 and TV/148.

1. INTRODUCTION

Exact reproduction of the colours contained within the gamut of the primaries used in a 3-colour additive process is possible only if the spectral sensitivities of the receptors controlling the primaries (normally expressed as 'analysis characteristics') have particular shapes decided by the chromaticities of the primaries. The ideal analysis curves for use with the standard NTSC primaries[1] are shown by the dotted curves (*a*) of Fig. 1. The only practicable method of approximately realizing such analysis curves is to arrange the optical system to split the light between the receptors in such a way as to give rather broad curves, and then to insert a linear matrix into the signal chain at some convenient point before gamma correction, so as to subtract from the signal corresponding to each primary colour proportions of the signals corresponding to the other two primaries. So far as is known, this procedure was not adopted in the past mainly because it would have entailed an increase in noise (it would also have been rendered inconvenient by the use of camera tubes such as the image orthicon and vidicon which do not provide linear signals); analysis curves with only positive lobes were therefore used.

If the analysis characteristics must be wholly positive the resulting colour errors can be reduced by making the curves somewhat narrower than the major positive lobes of the ideal curves. For example, curves (*b*) of Fig. 1 show the analysis specified in BBC Camera Specifications TV/126 and TV/148. Use of these narrower analysis curves results in a loss of sensitivity, and most manufacturers have therefore tended to use rather broader curves, such as curves (*c*) of Fig. 1, so as to effect a compromise between sensitivity and colour fidelity. It has been cal-

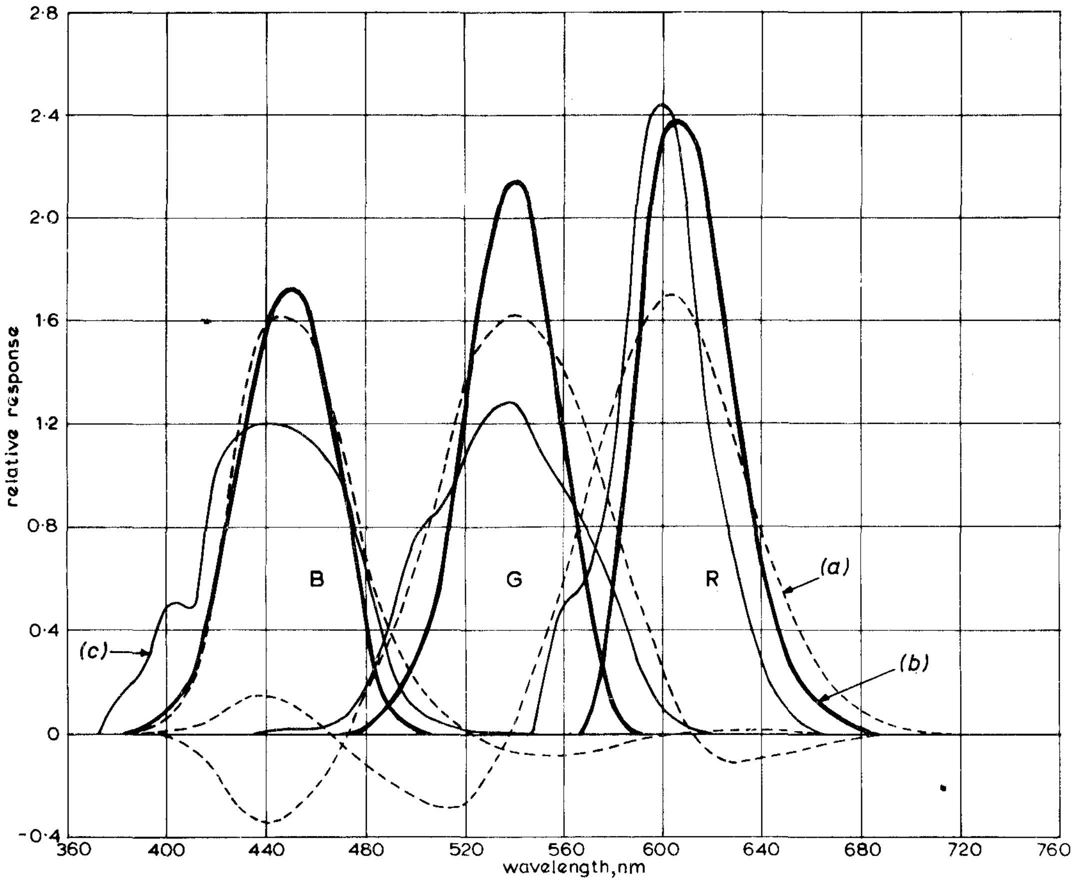

Fig. 1 - Analysis characteristics considered. Equi-energy, normalised to illuminant C

(*a*) Ideal analysis for NTSC primaries
(*b*) Analysis specified in TV/126 and TV/148
(*c*) Broader analysis curves typical of current practice

culated that the errors* resulting from analysis according to curves (*c*) may on average be expected to be about 30% greater than would have resulted from curve (*b*).

Until the introduction of the plumbicon, the principal tube used in colour cameras for studios was the image orthicon. For a number of reasons it is necessary so to operate such a camera that the charge on the target for peak white is the same pre-determined value for all three tubes. It follows that sensitivity and signal-to-noise ratio are independent and cannot be exchanged. Since the signal-to-noise ratio is in any case barely adequate for colour, a further loss due to matrixing cannot be accepted. On the other hand, use of the narrower analysis curves with positive lobes only (curves (*b*) of Fig. 1) is practicable provided that the light input can be increased.

The plumbicon tube if provided with sufficient light can give a signal-to-noise ratio in excess of the minimum requirement, and there is a useful range of light inputs in which signal-to-noise ratio and sensitivity can be exchanged. It follows that the increase in noise caused by matrixing might be offset by avoiding the loss of light implicit in the use of narrow analysis curves. Moreover the

* A quantitative definition of the errors is given in Section 2.

plumbicon has a linear transfer characteristic so that the introduction of a matrix would occasion little difficulty, the matrix would in fact precede gamma correction. The introduction of this tube therefore points to a re-examination of the possibility of matrixing.

An exact realization of the analysis depicted by curves (*a*) of Fig. 1 would result in too great a loss of sensitivity or increase in noise, and therefore some compromise is necessary. Determination of this compromise is not easy, since it is necessary to choose both the analysis curves given by the optical system and the elements of the matrix. As a first step it was decided to take the typical set of fairly broad analysis curves shown as curves (*c*) in Fig. 1 and determine what improvement in colour fidelity would result from the use of a matrix, and what penalty, in terms of sensitivity or signal-to-noise ratio, would be incurred.

2. METHOD

The method used to determine the optimum linear matrix involved an optimization of the reproduction of a number of test colours. Three sets of test colours were used, and it was hoped that each set could be considered to be a fair representation of the very large range of colours encountered in practice. The close agreement between the results obtained suggests that this was indeed so, considering that the sets were chosen in quite different ways.

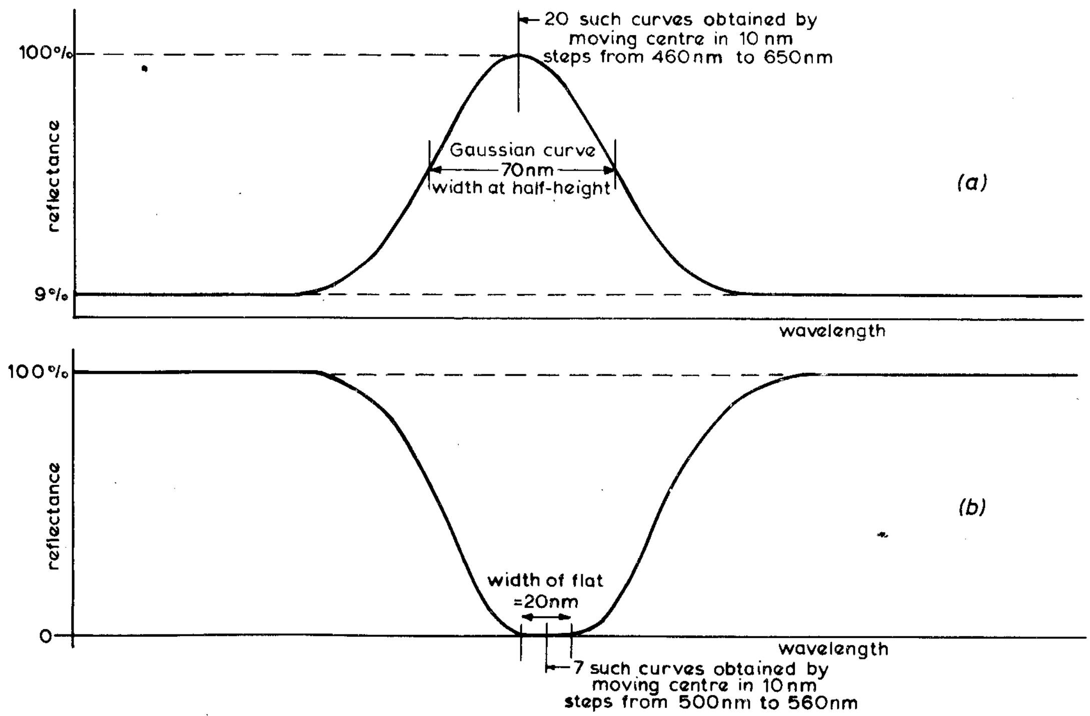

Fig. 2 - Fictitious reflectance characteristics used to define third set of colours

(*a*) Spectrum colours
(*b*) Magentas

The first set comprised the seven Courtauld fabric colours adopted by the E.B.U. for use when comparing colour television systems. The second set comprised sixteen colours, the eight used in the BBC Colour Test Light Box*, and eight others of similar hue to those in the Light Box but of about half the saturation. The third set comprised twenty-seven entirely fictitious colours. Twenty of these Fig. 2(*a*), were the colours produced by twenty different materials having approximately Gaussian shaped spectral reflectance curves, each one superimposed upon a uniform reflectance of 9%. The other seven Fig. 2(*b*), were the magentas produced by materials with trough-like spectral reflectance curves, the troughs being situated at seven different wavelength positions and having Gaussian shaped sides with flat bottoms of 20 nm width.

The chromaticities and luminances relative to that of peak white of each of the test colours in a set were calculated, together with the unity-gamma signal voltages R, G, and B necessary to reproduce them without error, using NTSC primaries. The signal voltages R_1, G_1 and B_1 resulting from the analysis corresponding to curves (*c*) of Fig. 1 were then calculated, and the chromaticities and relative luminances of the uncorrected reproductions were derived. The mean error was obtained as:

$$n = [\overline{n}_c^{\,2} + \overline{n}_L^{\,2}]^{\frac{1}{2}} \text{ jnd**}$$

where $\overline{n}_c$ is the mean chromaticity error and $\overline{n}_L$ is the mean luminance error. For each colour:

$$n_c = [(u_o - u_1)^2 + (v_o - v_1)^2]^{\frac{1}{2}} \; /0{\cdot}00384$$

(u_o, v_o) and (u_1, v_1) being the chromaticities of the original and reproduced colours expressed in terms of the 1960 CIE-UCS co-ordinates, and

$$n_L = [\log_e L_1 - \log_e L_o] \; /0{\cdot}0198$$

L_o and L_1 being the luminances of the original and reproduced colours relative to that of peak white.

The object of inserting the matrix was to reduce the mean error n as far as possible, that is, to convert R_1, G_1 and B_1 arising from the actual camera analysis into R, G and B, the signals required if the colour in question were to be reproduced accurately.

The matrix coefficients were derived by means of a computer programme that was divided into two parts. An approximate solution was first obtained by applying the method of least squares to sets of equations linking R, G, and B with R_1, G_1, and B_1. This was done partly to save computer time and partly to enable the accuracy of the result so obtained to be subsequently assessed.

The matrix required to transform R_1, G_1 and B_1 in to the three new values that we would like to be equal to R, G and B may be expressed as follows:

* A device for testing cameras and containing nine differently coloured filters illuminated from the rear.

** Just noticeable differences.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} a & b & c \\ d & e & f \\ g & h & j \end{bmatrix} \begin{bmatrix} R_1 \\ G_1 \\ B_1 \end{bmatrix}$$

where a to j are constants.

In order not to alter the reproduction of white, a unity matrix was ensured by putting $a + b + c = d + e + f = g + h + j = 1$. Therefore:

$$R = aR_1 + bG_1 + (1 - a - b)B_1 \text{ etc.}$$

Upon substituting the calculated values of R, G, B, R_1, G_1, B_1 into the above, three sets of N equations in two unknowns were obtained, N being the number of test colours used. Clearly if $N>2$ the equations cannot in general all be satisfied simultaneously. Nevertheless the method of least squares enabled a 'best fit' solution in one sense to be obtained.

However, the ultimate aim was not to minimise the errors existing between R_1, G_1, B_1 and R, G, B but to minimise n. The values a, b, c, etc. thus derived were then used as starting values in a slightly modified form of the Elliott 803 Library Programme for System Optimisation.* The computer was supplied with the sets of values u_0, v_0, L_0, R_1, G_1, B_1, together with the approximate values of a, b, c, etc. and instructions for calculating the mean error n. The quantities a, b, c, etc. were then allowed to vary in a controlled manner, after exploratory variations of a, e, and j in steps of 0·1% and of the others in steps of 0·25%, until the minimum value of n was reached. This minimum value, together with the associated matrix coefficients and the chromaticities and luminances of the colours as reproduced using the matrix, was printed out.

As a means whereby the effect of the matrix could be assessed, the reproductions resulting from an analysis using the optimum positive-only characteristics** were also calculated.

The whole procedure was carried out three times, using the three sets of test colours defined above.

3. RESULTS

It was found that a substantial improvement in the reproduction of all three sets of test colours could be obtained by the use of a matrix. Moreover the residual errors when the matrix was inserted were much less than would have resulted from an analysis using the optimum positive-only characteristics. This is indicated by the following table which gives the values of n obtained.

* This work was undertaken by Mr. R.W. Lee.

** Although referred to as optimum, these are not necessarily the best positive-only analysis characteristics for cameras, but it is believed that they are close to the best possible. They are very similar to those specified in TV/126 and TV/148, the peak of the blue sensitivity curve being at 457 nm, and the blue/green crossover wave-length being at 503 nm.

TABLE 1

n, JNDS	TEST COLOURS			ANALYSIS CURVES USED FOR OBTAINING R_1, G_1, B_1
	1st SET	2nd SET	3rd SET	
Uncorrected analysis	9•74	7•88	9•06	curves (c)
Optimum positive-only analysis	6•07	6•35	8•30	curves (b)
Corrected analysis (each set using its own optimised matrix)	3•05	2•01	2•94	curves (c)
Corrected analysis using optimum matrix for 2nd set of colours	3•57	2•01	3•41	curves (c)

It was noted with interest that the matrices resulting from the preliminary least-squares calculation had coefficients very similar to those finally obtained. The corresponding values of n were in fact only of the order of 7% greater than the final values.

The three final matrices used for the results given in the third line of Table 1 were as follows:

for the first set of colours,

$$\text{Matrix No. 1} \qquad \begin{bmatrix} 1{\cdot}20 & -0{\cdot}24 & 0{\cdot}04 \\ -0{\cdot}03 & 1{\cdot}24 & -0{\cdot}21 \\ -0{\cdot}03 & 0{\cdot}01 & 1{\cdot}02 \end{bmatrix}$$

for the second set of colours,

$$\text{Matrix No. 2} \qquad \begin{bmatrix} 1{\cdot}12 & -0{\cdot}16 & 0{\cdot}04 \\ -0{\cdot}02 & 1{\cdot}23 & -0{\cdot}21 \\ -0{\cdot}02 & -0{\cdot}01 & 1{\cdot}03 \end{bmatrix}$$

for the third set of colours,

$$\text{Matrix No. 3} \qquad \begin{bmatrix} 1{\cdot}12 & -0{\cdot}15 & 0{\cdot}03 \\ 0{\cdot}05 & 1{\cdot}21 & -0{\cdot}26 \\ -0{\cdot}07 & 0{\cdot}01 & 1{\cdot}06 \end{bmatrix}$$

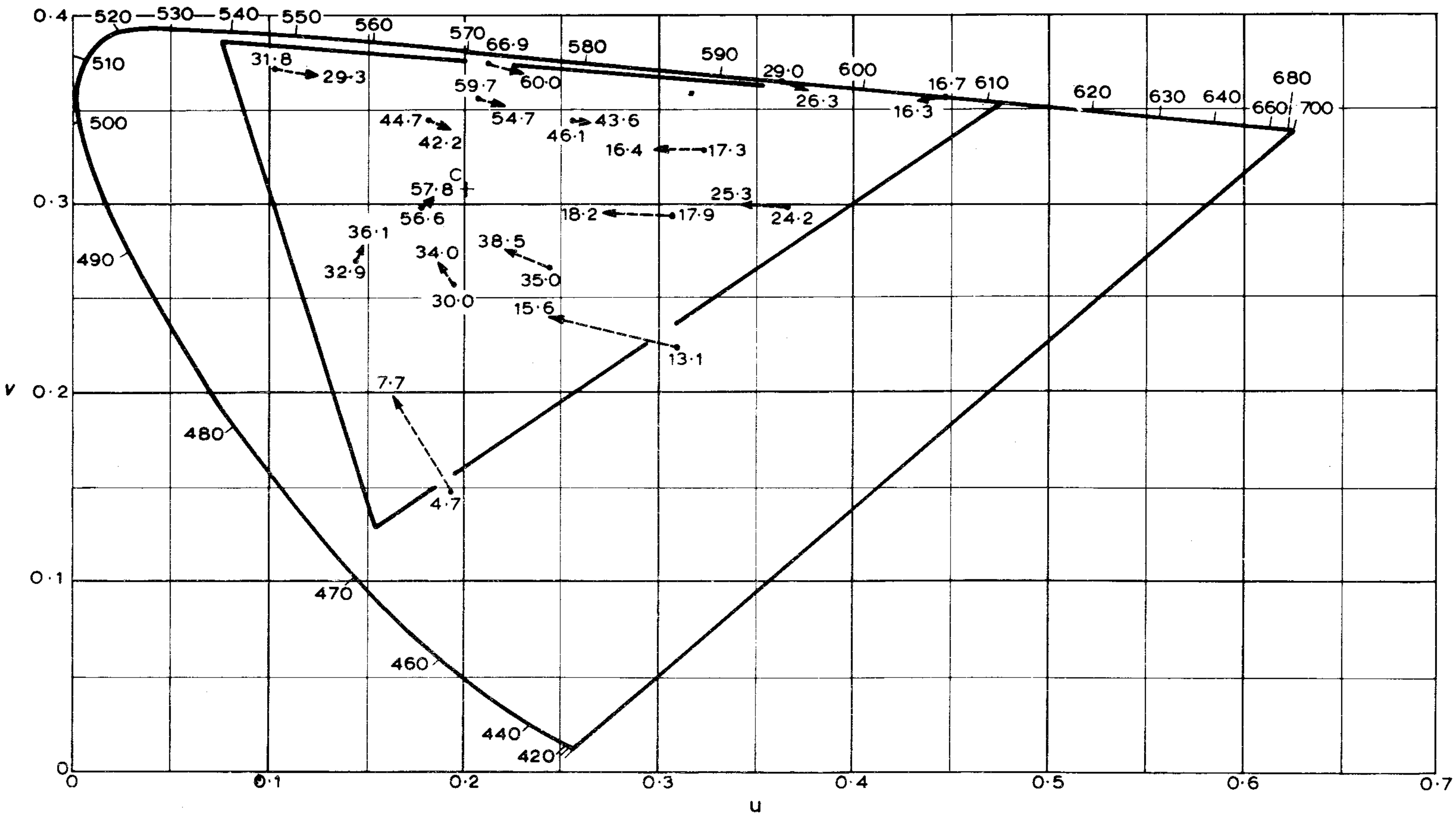

Fig. 3 - Reproduction of second set of test colours using the broader analysis characteristics (curves (c) of Fig. 1). Synthesis by NTSC primaries

Reproduced colours at arrow heads:
Figures are relative luminances expressed as percentages
Error figure n = 7·88 jnd

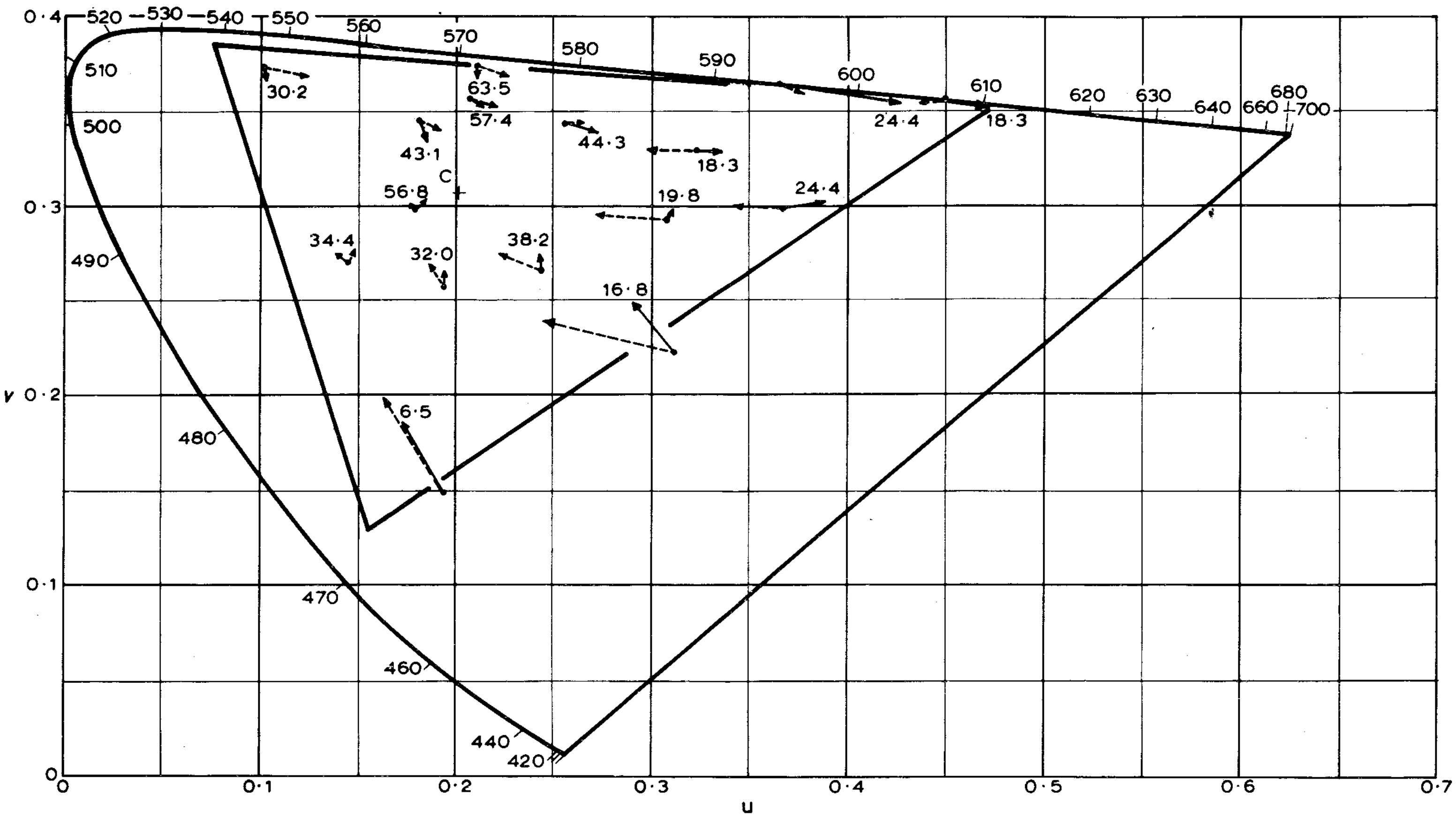

Fig. 4 - Comparison of reproduction of second set of test colours using optimum positive-only analysis characteristics (curves (b) of Fig. 1) with that obtained using the current broader analysis characteristics (curves (c) of Fig. 1). Synthesis by NTSC primaries

Reproduced colours at arrow heads:

←—— Reproduction using optimum positive-only analysis. Error figure n = 6·35 jnd

←- - - - - Reproduction using camera analysis

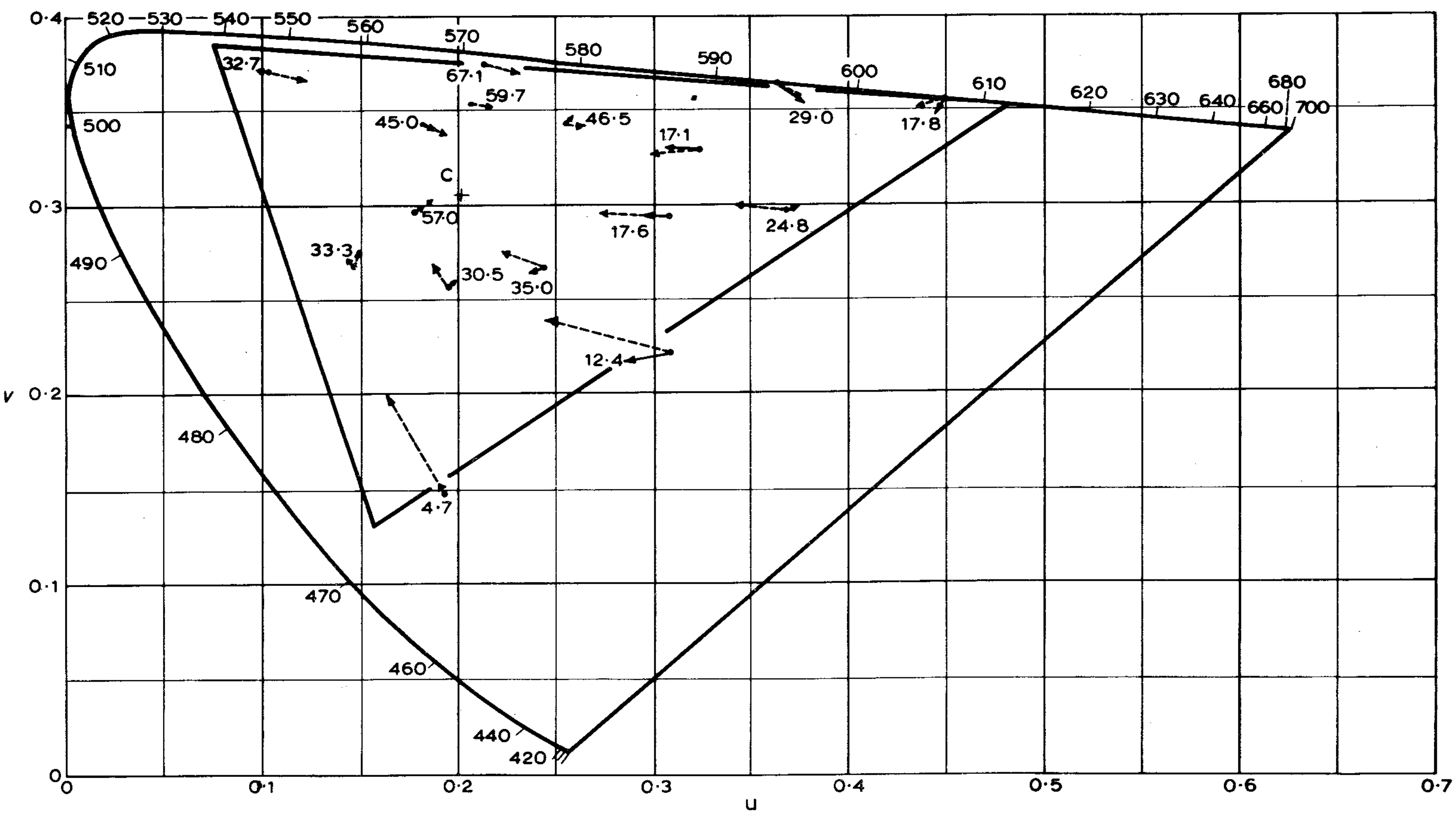

Fig. 5 - Comparison of reproduction of second set of test colours using the broader analysis characteristics (curves (c) of Fig. 1) and linear matrix No. 2 with that obtained without the matrix. Synthesis by NTSC primaries

Reproduced colours at arrow heads:
⟵ Reproduction using matrix. Error figure n = 2·01 jnd
⟵------ Reproduction without matrix

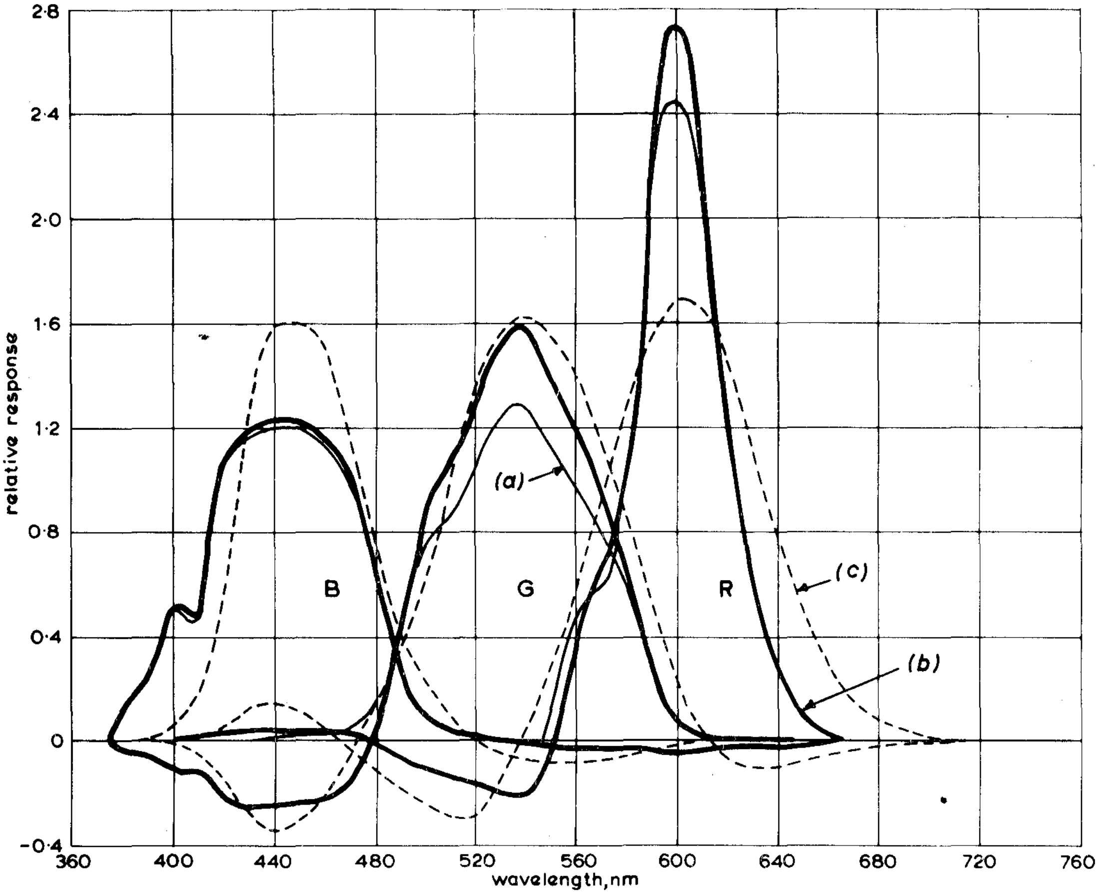

Fig. 6 - Effect of matrix No. 2 on analysis of camera

(*a*) Uncorrected camera analysis
(*b*) Analysis with matrix inserted
(*c*) Ideal analysis for NTSC primaries

Since the second set of test colours contained a number of desaturated ones it can probably lay the best claim to being a representative set. Moreover, as the last row of Table 1 also shows, the matrix obtained using the second set of colours improves the reproduction of the first and third set by almost the same amount as do the matrices best suited to the first and third set. It is therefore proposed that the second matrix be used.

Figs. 3, 4 and 5 show in greater detail the results of the calculations based on the second set of colours.

The second matrix modifies the analysis characteristics of the camera in the manner shown in Fig. 6. With the matrix connected, curves (*b*), the green analysis approximates much more closely to the ideal, curves (*c*), and negative lobes are produced in the region of the larger negative lobes featured in the ideal analysis.

When NTSC phosphors are used, the luminance of the displayed colour is given by:

$$Y = 0{\cdot}299R + 0{\cdot}587G + 0{\cdot}114B$$

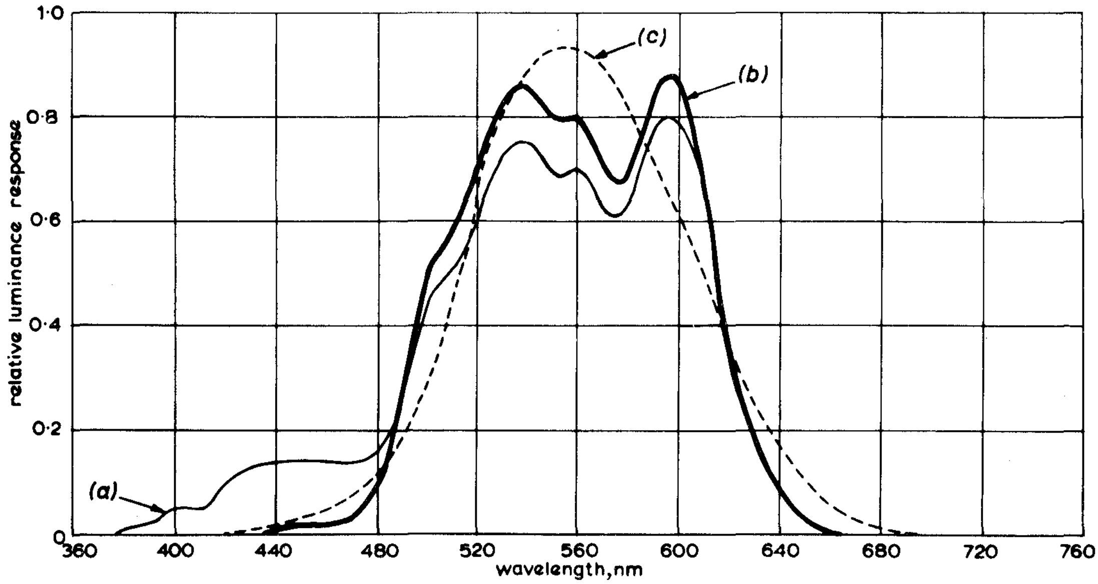

Fig. 7 - Effect of matrix No. 2 on equivalent luminance characteristic of camera

(*a*) Uncorrected characteristic
(*b*) Characteristic modified by matrix
(*c*) Photopic response

In the absence of a matrix, therefore, the relative contributions of equi-energy spectral components to the displayed luminance are given by:

$$Y(\lambda) = 0{\cdot}299R(\lambda) + 0{\cdot}587G(\lambda) + 0{\cdot}114B(\lambda)$$

where $R(\lambda)$, $G(\lambda)$ and $B(\lambda)$ are the analysis characteristics of the camera.

The luminance characteristic of an uncorrected camera using the analysis curves (*c*) of Fig. 1 is plotted as curve (*a*) of Fig. 7. It should be compared with curve (*c*) which shows $\bar{y}(\lambda)$, the photopic response of the eye, this being the ideal luminance characteristic of a colour reproducing system.

When the matrix is used, $Y(\lambda)$ becomes equal to:

$$0{\cdot}321R(\lambda) + 0{\cdot}673G(\lambda) + 0{\cdot}006B(\lambda)$$

which is plotted as curve (*b*) of Fig. 7. It will be seen that the formerly excessive blue response has been reduced, and that the characteristic now approximates more closely to the ideal.

It has been estimated that if the level of scene illumination is just sufficient to cause peak output in the green (most sensitive) channel of the camera when a white is displayed, the signal-to-noise ratios* in the red, green and blue channels are of the order:

31·9 dB (red), 44·8 dB (green), and 33·3 dB (blue)

The noise produced in the plumbicon tube has a triangular spectrum. Moreover the coding system by which the colour signal is transmitted to the viewer con-

* Peak picture signal voltage divided by r.m.s. noise voltage

tains low-pass filters which limit the bandwidth of the chrominance components. Thus the noise visible to the viewer is almost entirely conveyed by the luminance component. In this discussion no account is taken of the results of the sharing of the luminance band by the modulated chrominance signal.

When a white is displayed, and before the matrix is connected, the luminance noise present is given by:

$$0{\cdot}299r + 0{\cdot}587g + 0{\cdot}114b,$$

where r, g and b are the uncorrelated noise voltages from the red, green and blue head amplifiers. Assuming the signal channel noise levels quoted above, the luminance signal-to-noise ratio* in the absence of a matrix is therefore 41·1 dB.

As explained above, the matrix modifies the amounts of red, green and blue signals from the camera which make up the luminance component of the composite colour signal. Thus when the matrix is inserted, the luminance noise is given by:

$$0{\cdot}321r + 0{\cdot}673g + 0{\cdot}006b,$$

and this results in a luminance signal-to-noise ratio of 41·0 dB.

This deterioration in signal-to-noise ratio is very small because the signals from which the luminance component is composed are accompanied by noise signals which, when a matrix is used, are no longer completely uncorrelated. For example, the noise present at the green signal output terminal of the matrix contains a component contributed by the blue camera channel. This component is in antiphase with the noise signal originating in the blue camera channel and accompanying the blue signal obtained from the matrix. When the luminance component of the composite signal is subsequently composed, there is a partial cancellation of such antiphase noise components. Therefore although matrixing degrades the signal-to-noise ratio of each of the three colour separation signals, and in particular that of the luminance component of the composite signal, the noise observed in the final picture is distributed differently. Most of the increase is allocated to saturated colours (and it should be noted that the luminance component corresponding to such colours already contains increased noise due to the gamma correction of primary colour signals of near-zero amplitude). Greys and desaturated colours, however, are hardly affected.

However, it has been calculated that if under the foregoing or inferior lighting conditions (for which the level of scene illumination was just sufficient to cause peak output in the green channel of the camera when a white was displayed) the camera analysis defined in TV/126 and TV/148, curves (*b*) Fig. 1, were used in place of curves (*c*) in Fig. 1, the resulting loss of sensitivity would cause reductions in signal-to-noise ratios of 2·5 dB (red), 6·2 dB (green), 0·4 dB (blue), and 3·1 dB (luminance).

If the illumination of the scene is sufficient, it is advantageous to insert a neutral filter into the optical path leading to the 'green' plumbicon tube so as to limit the inequality between signal currents and thus to obtain a larger output

* Defined as the signal-to-noise ratio of the luminance component of the composite signal corresponding to peak white in the scene.

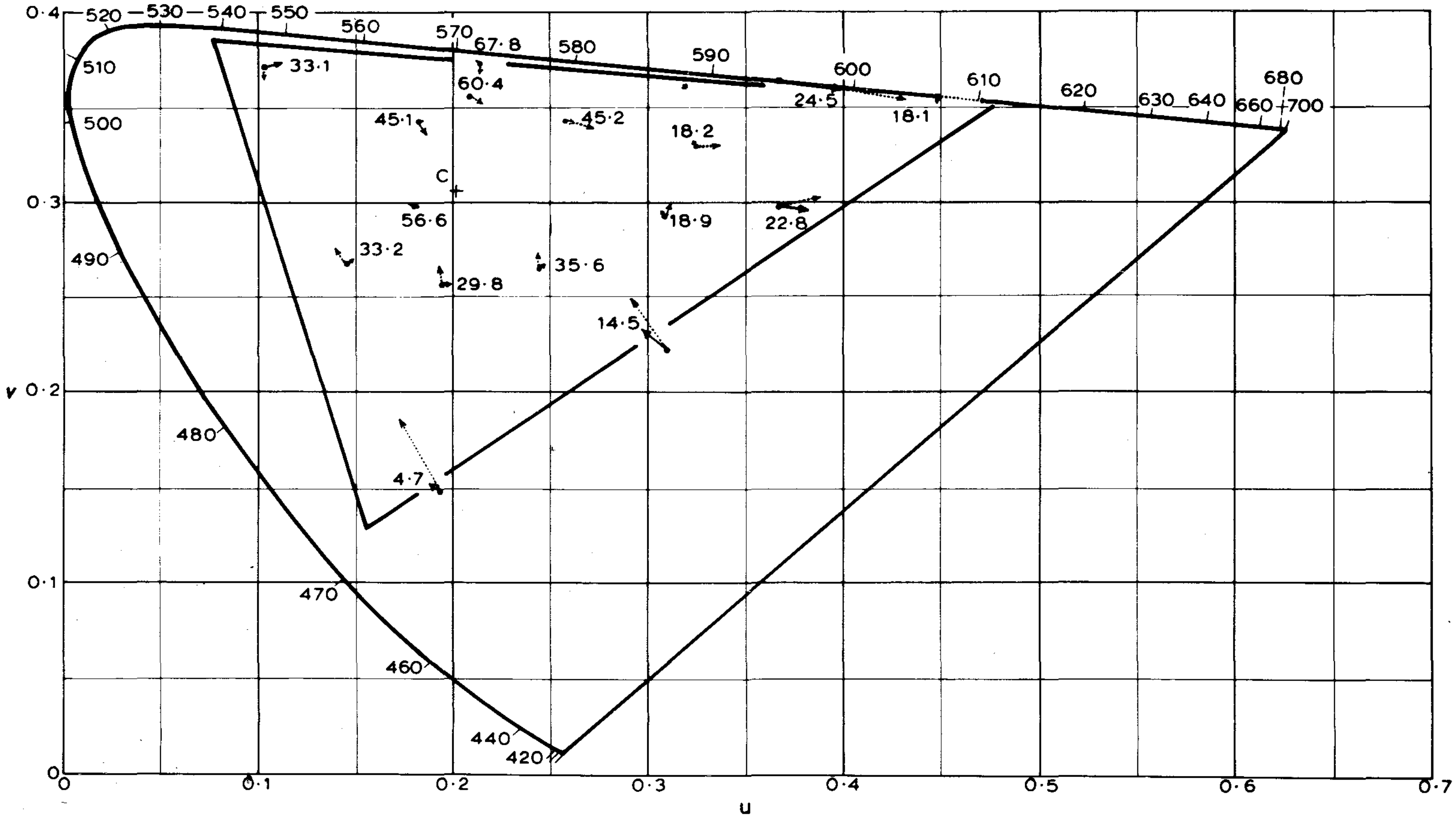

Fig. 8 - Comparison of reproduction of second set of test colours using optimum positive-only analysis (curves (b) of Fig. 1) and a linear matrix readjusted to optimum with that obtained without the matrix. Synthesis by NTSC primaries

Reproduced colours at arrow heads:
← Reproduction using matrix. Error figure n = 2·67 jnd
←······ Reproduction without matrix

signal from the red and blue tubes without overloading the green channel. By this means the signal-to-noise ratios of all three camera channels may be made equal to about 41 dB (regardless of the analysis characteristics). When this is done, insertion of the recommended matrix causes a deterioration in luminance signal-to-noise ratio of about 1 dB.

An important practical point is that the matrix could be inserted or taken out at the turn of a switch. Thus, in outside broadcast use for instance, where the illumination is sometimes very poor, and where the increased colour fidelity is not considered worthwhile in view of the increase of noise in saturated colour regions, the camera could easily be made to revert to its original wideband analysis.

Since the camera analysis obtained using the matrix resulted in a colour reproduction markedly superior to that resulting from the optimum positive-only analysis, it was considered of interest to investigate the extent to which the latter analysis could be improved by a linear matrix. The computations were therefore repeated with the optimum positive-only analysis substituted for the present camera analysis.

It was found that a matrix best suited to the optimum positive-only analysis would reduce the value of n appropriate to the second set of test colours from 6·35 to 2·67. Thus a considerable improvement is possible, but the final result is not superior to that obtained using the broader analysis characteristics at present adopted for the camera together with Matrix No. 2. Fig. 8 shows this result in greater detail, and should be compared with Fig. 4.

4. CONCLUSIONS

Both colorimetric and noise considerations lead to the view that it is better to use somewhat broad analysis characteristics such as curves (*c*) of Fig. 1, together with a matrix, rather than to use the narrower analysis characteristics specified in TV/126 and TV/148. It has been estimated that the addition of such a matrix would enable colour errors to be reduced on average to between one third and one quarter of their present magnitude. A small deterioration in signal-to-noise ratio is produced, but the distribution of noise within the picture is altered so that desaturated areas are hardly affected.

The broad analysis curves (curves (*c*) of Fig. 1) were not designed with a view to using a matrix, and are therefore not necessarily the best for this purpose. Further work is required to establish the best optical analysis together with the best matrix, taking into account colour fidelity, noise performance, and ease of instrumentation.

5. REFERENCE

1. 'Colour Television: The Adaptation of the NTSC System to U.K. Standards Part 1: The Colorimetry of Analysis and Synthesis', BBC Research Report No. T-060/1, 1956/30.

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